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Volume II

THE USER'S MANUAL OF AN INTERACTIVE GRAPHICS CRACK GROWTH ANALYSIS PROGRAM
VOLUME II - INTERACTIVE CRKGRO

J. B. Chang
K-W Liu

Rockwell International
North American Aircraft Operations
P.O. Box 92098
Los Angeles, CA 90009

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This technical report has been reviewed and is approved for publication.

Robert M. Engle Jr.
Project Engineer

Davey L. Smith, Chief
Structural Integrity Branch

FOR THE COMMANDER:

RALPH L. KUSTER Jr., Colonel, USAF
Chief, Structures & Dynamics Division

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This report presents a description of a computer program to be operated interactively in the INTERCOM environment on CDC CYBER computer system. This program is the interactive graphics version of a detailed-level crack-growth analysis program CRKGRO, with an additional capability of inputing the user-coded stress intensity factor solution used for the fatigue crack-growth analysis.

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FOREWORD

This report presents a description of a computer program to be operated interactively in the INTERCOM environment on the CDC CYBER computer system. This program is the interactive graphics version of the CRKGRO program developed under a research program entitle "Improved Methods for predicting Spectrum Loading Effects." This program was administered by the Flight Dynamics Laboratory of the Air Force Wright Aeronautical Laboratory, Wright-Patterson Air Force Base, Ohio, under Contract F33615-77-C-3121, Project 2401, "Structural Mechanics," Task 240101, "Structural Integrity for Military Aerospace Vehicles," Work Unit 2401020, "Improved Methods for Predicting Spectrum Loading Effects."

This research program was primarily conducted by personnel from the Fatigue and Fracture Mechanics Group, Dynamics Technology, Structure Systems, supervised by George E. Fitch, Jr., supervisor, Joseph S. Rosenthal, manager, and Dr. Leslie M. Lackman, director. James B. Chang was the program manager and principal investigator. R. Fink was responsible for the initial program development.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Section I

INTRODUCTION

The INTERACTIVE-CRKGRO program is a streamlined fatigue crack-growth analysis computer code that operates interactively in the INTERCOM[1] environment on the CDC CYBER computer system. This program is the interactive version of the detailed-level crack-growth analysis program, CRKGRO[2] wtih an additional capability of inputting user-coded stress intensity factor solutions used for the crack-growth analysis.

In recent years, crack-growth analysis has become important throughout the life cycle of any aircraft system since the Air Force philosophy for achieving the structural integrity of airplanes has employed damage-tolerance and durability requirements. A crack-growth program with an interactive capability will provide realtime feedback schemes for users to observe and influence change on the particular growth history, and will certainly enhance evaluation of crack-growth behavior in any phases of design, even as early as the preliminary design stage.

The crack-growth methodology implemented in CRKGRO is based on linear elastic fracture mechanics principles with the assertion that the primary parameter which controls the growth of a crack is the stress intensity factor range (ΔK) at the crack tip. Although there is a wide variety of stress intensity factor (K) solutions available in the program for various crack configurations, the option to enable the user to input the user-coded stress intensity factor solution will undoubtedly add to the program a great versatility, especially in the evaluation of a new stress intensity factor solution during the K-solution development stage.

This manual presents information needed to use INTERACTIVE-CRKGRO and provides input and output guidance to the users. Users are advised to refer to CRKGRO User's Manual[2] for more detailed background of crack growth analysis procedures and input/output descriptions.

Section II

COMPUTER PROGRAM DESCRIPTION

INTERACTIVE-CRKGRO uses the CDC time-sharing software package INTERCOM [1] and the TEKRONIX plotting software package PLOT-10 [3] to provide an interactive capability of the crack-growth program, CRKGRO. In addition, the CDC program library management software package UPDATE [4] provides users access to the INTERACTIVE-CRKGRO source program library to implement an additional feature of allowing users to insert user-defined stress intensity factor solutions into the INTERACTIVE-CRKGRO subroutine for subsequent computation. INTERACTIVE-CRKGRO, contains the following features not available in CRKGRO:

1. Allows inputs from a specified data set and terminal instead of from punched cards
2. Allows tabular outputs to be displayed on the terminal screen and provides hard copies
3. Allows graphical outputs to be displayed on the terminal screen and provides hard copies
4. Allows users to input user-defined stress intensity factor solutions in a self-contained format on site

INTERACTIVE-CRKGRO is written in FORTRAN IV and programmed in modular form with the placement and retrieval of data through common statements and local files. The main modules consist of nine subroutines: INPUT, OUTPUT, CRIT, CYCCNT, GROW, PTPARM, PLOT, K10XX, and K20XX. A brief description of each of these modules follows:

INPUT Reads the input data consisting of crack growth rate constants, and load interaction parameters, fracture properties and load or stress spectrum, etc

OUTPUT Prints the echo of the input data

CRIT Computes the critical crack length

CYCCNT	Range-pair counts the stress spectrum
GROW	Computes the crack-growth history data
PTPARM	Plots the crack-growth history data in four forms
PLOT	Plots the grid, scaling, and data point for PTPARM
K10xx	Stress intensity factor library for part-through cracks
K20xx	Stress intensity factor library for through-the-thickness cracks

A list of the code number assigned to each crack configuration contained in the present K-library is shown in Figure 1.

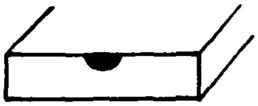
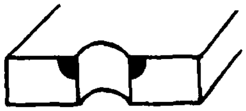
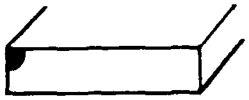
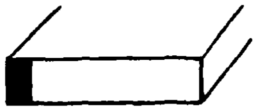
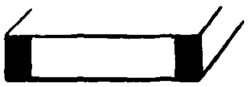
CODE NO.	DESCRIPTION	GEOMETRY
1010	SURFACE CRACK, CENTERED	
1030	ONE CORNER CRACK FROM CENTERED OPEN HOLE	
1050	TWO CORNER CRACKS FROM CENTERED OPEN HOLE	
1070	ONE CORNER EDGE CRACK	
1090	USER-DEFINED PART-THROUGH-CRACK STRESS INTENSITY FACTOR SOLUTION	
2010	THROUGH-CRACK, CENTERED	
2020	ONE THROUGH-CRACK FROM CENTERED OPEN HOLE	
2030	TWO THROUGH-CRACKS FROM CENTERED OPEN HOLE	
2040	ONE THROUGH-EDGE CRACK	
2050	TWO THROUGH-EDGE CRACKS	
2060	ASTM STANDARD CT SPECIMEN	
2090	USER-DEFINED THROUGH-CRACK STRESS INTENSITY FACTOR SOLUTION	

Figure 1. Crack Library

Section III

INPUT AND OUTPUT DESCRIPTION

INTERACTIVE-CRKGRO accepts input data from two sources. The primary source is the terminal keyboard, through which the user types in data in response to each input query from the program. The alternate form of input is through an external data file. This file contains the card images of the input data that would normally be supplied via the terminal keyboard, and must be a cataloged permanent file. The latter scheme provides easy correction, modification, and editing of the input data.

Each input query is as self-explanatory as possible. Tl :irst query at the very beginning of INTERACTIVE-CRKGRO is whether the user- 'ined stress intensity factor solution option is elected. If such an opt: is to be used, user-defined stress intensity factor solution input is :ired, first for the part-through-crack (if any) and then for the through ickness crack solution. A play-by-play description of this option fo...ws:

- WELCOME TO INTERACTIVE-CRKGRO PROGRAM VERSION 1.0.

- ENTER FILE NAME FROM CRACK GROWTH INPUT.

  (Enter "INPUT." if crack-growth input data are to be entered from terminal keyboard.

  Enter the logical file name of the external data file containing the crack growth input data.

  NOTE: All file names must end with a period; otherwise, there will be a control card error.)

- DO YOU WISH TO ENTER YOUR OWN STRESS INTENSITY FACTOR EQUATION?

  ENTER "YES OR "NO." (Self-explanatory)

- IS YOUR STRESS INTENSITY FACTOR FOR THE PART-THROUGH CRACK? ENTER "YES" OR "NO". (Self-explanatory)

- ENTER YOUR PART-THROUGH CRACK STRESS INTENSITY FACTOR EQUATION

  1-------------7---

(If the previous entry is YES, then this query appears. Enter the user-defined stress intensity factor equations in FORTRAN statements in Column 7 through 72. Column allocations are shown in numeral dotted points).

- o IS THE STRESS INTENSITY FACTOR FOR THE THROUGH CRACK? ENTER "YES" OR "NO?"

  (Self-explanatory)

- o ENTER THE THROUGH-THE-THICKNESS CRACK STRESS INTENSITY FACTOR EQUATION

  1-----7---

  (Same as previous query)

To input a user-defined stress intensity factor solution, the user is restricted to the following variables:

AOC	Crack depth over crack length ratio
ADT	Crack depth over thickness ratio
APL	Crack depth
APREP	Stress intensity factor solution in depth direction/σ
CPL	Crack length
CPREP	Stress intensity factor solution in length direction/σ
HALFW	Half width of structure
PI	π (3.14159)
Q	Shape factor
RADIUS	Radius of hole
T	Thickness

Since the compilation of a new stress intensity factor subroutine uses a CDC compiler, the user is allowed to use any mathematical routines available on the compiler.

INTERACTIVE-CRKGRO provides both one-dimension (1-D) and two-dimension (2-D) crack growth options for a part-through crack. For the 2-D option, when a user-defined K-factor solution mode is executed, both APREP and CPREP should be defined. For the 1-D option, only APREP needed to be defined. In addition, a through-the-thcikness crack user-defined stress intensity solution is recommended. In the case where a breakthrough (transition from part-through-crack to through-the-thickness crack) has occurred, the program will automatically switch from the part-through-crack subroutine to the through-the-thickness crack subroutine. If CPREP is not defined in the through-the-thickness crack routine, CPREP will be set equal to zero as a result, there will be zero crack growth in the length direction once the cracks have broken through.

Crack-growth life computation input consists of eight segments or options with labeled keywords as follows:

1. TITLE: Problem title and description
2. MATERIAL: Material properties and crack-growth rate constants and parameters
3. GEOMETRY: Structure geometry and load interaction effects
4. SPECTRUM: Spectrum inputs and spectrum information
5. OUTPUT: Establishes level of print and graph desired
6. REPLOT: To obtain desired plots from crack-growth data saved from previous analysis
7. END DATA: Defines end of input data and begins crack growth life computation
8. ENDJOB: Defines end of job and terminates program

With the exception of segments 7 and 8, the order of these input segments is immaterial to the program. These segment inputs can be overwritten by reentering to the segment where changes are to be made and entering the necessary in puts. Program execution will be based upon the last input of each segment.

The following are the play-by-play descriptions of each input segment for performing crack-growth life analysis:

1. OPTION: TITLE

o ENTER TITLE CARD (MAX OF 70 CHARACTERS).

? Any alphanumeric information which the user desires to input for problem identification.

2. OPTION: MATERIAL

o ENTER MATERIAL TITLE CARD (MAX OF 60 CHARACTERS).

(Self-explanatory)

o ENTER DC/DN CRACK-GROWTH RATE EQUATION COEFFICIENT.

? (Enter the crack-growth rate equation component C_c used in dc/dN equation.)

o ENTER DC/DN CRACK-GROWTH RATE EQUATION EXPONENT.

? (Enter crack-growth rate equation N_c used in dc/dN equation.)

o ENTER DA/DN CRACK-GROWTH RATE EQUATION COEFFICIENT.

? (Enter crack-growth rate equation coefficient C_a used da/dN equation)

o ENTER DA/DN CRACK-GROWTH RATE EQUATION EXPONENTS.

? (Enter crack-growth rate equation exponent N_a used in da/dN equation.)

o ENTER CRACK-GROWTH RATE EQUATION EXPONENTS:

'M' for positive stress ratio

? (Enter m, for positive stress ration collapsing factor m used in modified Walker equation.)

'Q' for negative stress ratio

? (Enter negative stress ratio acceleration index q used in Chang equation.)

- o ENTER THE FRACTURE TOUGHNESS FOR HALF CRACK LENGTH 'C'

  ? Plane stress or transition mode fracture toughness, K_c (KSi $\sqrt{in}$) used for through-crack instability criteria on crack length C.

- o ENTER THE FRACTURE TOUGHNESS FOR CRACK DEPTH 'A'.

  ? Plane strain fracture toughness, K_{IC}(ksi$\sqrt{in.}$) used for part-through-crack instability criteria on crack depth a.

- o ENTER MATERIAL YIELD STRENGTH IN KSI.

  (Self-explanatory)

- o ENTER VALUE OF DELTA K THRESHOLD.

  ? The threshold of Δk (ksi$\sqrt{in.}$)

- o ENTER THRESHOLD CONSTANT A.

  ? (Enter "ZERO" for a constant threshold, and a non-zero threshold constant if a variable threshold is used.)

- o ENTER POSITIVE STRESS RATIO CUTOFF VALUE.

  ? (Enter cutoff value of positive stress ratio, R^+_{cut}, below which material is assumed to have no stress ratio layering effect on crack growth; value between .0 and 1.)

- o ENTER NEGATIVE STRESS RATIO CUTOFF VALUE.

  ? (Enter cutoff value of negative stress ratio, R^-_{cut}, above which material is assumed to have no acceleration effect on crack growth; value between -1. and 0.)

3. OPTION: GEOMETRY

- o LOAD INTERACTION CONTROL - ENTER "NO", "YES", or "BOTH".

  ? (If "NO" is input, no load interaction will be considered, and compressive stress will be set to zero in the analysis. If "YES" is input, retardation and compression acceleration will be considered. If "BOTH" is input, both analyses will be performed.)

- o ENTER OVERLOAD SHUTOFF RATIO.

  ? (Self-explanatory)

- o ENTER CRACK CODE.

  ? (See Figure 1.)

- o ENTER WIDTH OF SPECIMEN (INCH)

  ? (Self-explanatory)

- o ENTER THICKNESS OF SPECIMEN (INCH)

  ? (Self-explanatory)

- o ENTER RADIUS OF HOLE (INCH, IF NO HOLE, ENTER 0.0).

  ? (Self-explanatory)

- o ENTER TRANSITION CODE - (0) WHEN CRACK EQUALS THICKNESS
  (1) BEFORE CRACK EQUALS THICKNESS

  ? (Control for transition from part-through crack to a through crack)

- o ENTER INITIAL CRACK LENGTH (INCH)

  ? (Self-explanatory)

- o ENTER FINAL CRACK LENGTH (INCH), IF NO FINAL CRACK LENGTH, ENTER 0.0.)

  ? (Self-explanatory)

- o ENTER NUMBER OF LIMIT STRESSES (MAXIMUM OF 7).

  ? (Self-explanatory)

- o ENTER LIMIT STRESSES (ksi).

  ? (Self-explanatory)

- o CONTROL FOR DETERMINING WHEN INSTABILITY IS REACHED IS:

  1 - BY LIMIT STRESS INTENSITY FACTOR
  2 - BY MAXIMUM STRESS INTENSITY FACTOR

  (Self-explanatory)

4. OPTION: SPECTRUM

o ENTER SPECTRUM TITLE (MAXIMUM OF 70 CHARACTERS)

? (Self-explanatory)

o ENTER SPECTRUM FACTOR.

? (Factor used to scale the spectrum, i.e., all stresses are increased by this factor)

o ENTER RANGE - PAIR COUNTING CONTROL.

0 - NO RANGE PAIR COUNTING
1 - RANGE PAIR COUNTING

? (Self-explanatory)

o ENTER UNIT NUMBER FOR INPUT OF SPECTRUM.

? (Enter "5" if spectrum is to be input from terminal keyboard. Enter file unit number where spectrum is to be read in from external file.)

o THE FLIGHT SPECTRUM SEGMENT TYPES ARE:

MAX-MIN R-DELTA MEAN END
ENTER SEGMENT TYPE

("MAX-MIN" - Maximum and minimum stresses spectrum are input
"R-DELTA" - Stress ratio and delta stress spectrum are input
"MEAN" - Mean and alternate stresses
"END" - Defines end flight segment spectrum)

o ENTER MISSION-MIX DEFINITION.

? MISSION = NBLKS (factor i and segment i)
NBLKS - Number of times the complete mission string is repeated
FACTORi - Number of times individual flight segment is repeated
SEGMENTi - Mission segment number preceded by the letter "s" for segment
Sample: Mission = 100 (3S1 + 4S2)

o ENTER NUMBER OF FLIGHTS PER BLOCK.

? (Self-explanatory)

5. OPTION: OUTPUT

- IS THE SPECTRUM TO BE PRINTED? "YES" or "NO."

  ? (Self-explanatory)

- PRINT CRACK GROWTH HISTORY DATA IN INCREMENTS OF ------BLOCKS.

  ? Control for printing the crack growth history in increments of NB number of blocks.

- IS PLOTTING TO BE DONE? "YES" or "NO".

  ? (If "NO" is input, the program will skip the following plotting questions)

- SPECIFY TYPE OF PLOTS YOU WOULD LIKE - A VS F.

  ? (Enter "YES" or "NO")

- DA/DF vs F.

  ? (Enter "YES" or "NO")

- DA/DF vs A.

  ? (Enter "YES" or "NO")

- DA/DF vs K_{max}/Flt.

  ? (Enter "YES" or "NO")

- SPECIFY TYPE OF GRID DESIRED.

- FOR X-AXIS, ENTER 0 - LINEAR OR 1 - LOG.

  ? F-axis of A vs F plot

- FOR Y-AXIS, ENTER 0 - LINEAR OR 1 - LOG.

  ? A-axis of A vs F plot

- FOR X-AXIS, ENTER 0 - LINEAR OR 1 - LOG.

  ? F-axis of DA/DF vs F plot

o FOR Y-AXIS, ENTER 0 - LINEAR OR 1 - LOG.

? DA/DF axis of DA/DF vs F plot

o FOR X-AXIS, ENTER 0 - LINEAR OR 1 - LOG.

? A-axis of DA/DF vs A plot

o FOR X-AXIS, ENTER 0 - LINEAR OR 1 - LOG.

? K_{max}/Flt axis of DA/DF va K_{max}/Flt plot

o FOR Y-AXIS, ENTER 0 - LINEAR OR 1 - LOG.

DA/DF axis of DA/DF vs K_{max}/Flt plot

o SHALL THE SLOW GROWTH RATE STEPS BE BYPASSED? "YES" or "NO".

? (If "YES" is input, the program will bypass steps with growth rate less than 10^{-8} and $\Delta K < 2\ \Delta K_{max}$.)

o SHALL THE STRESS INTENSITY EQUATIONS BE PRINTED? "YES" or "NO".

? (This option does not work if user-defined stress intensity factor solution is inputed. This option is not available when the user-defined stress intensity factor solution option is invoked.)

o SHALL THE GROWTH DATA OF THE FIRST BLOCK BE PRINTED? "YES" or "NO".

? (Self-explanatory)

o ENTER NUMBER OF STEPS TO BE PRINTED IN REQUESTED PRINT BLOCK.

? (Control for printing intermediate growth history - i - growth of the first ith steps of each "NB" - th blocks will be printed.

-i - growth of the first i^{th} steps of each "NB" block will be printed.

+i - growth of the last i^{th} steps of each "NB" th block will be printed

0 - all steps of "NB" th block will be printed.)

6. OPTION: END DATA

This will define the end of input data and begin crack-growth life computation.

WHEN A'?' IS PRINTED ON SCREEN, ENTER A "P", AND PRESS RETURN, TO START PRINTING OR TO CONTINUE PRINTING.

The output consists of input echo data and computed results. The latter can be classified as either graphical displays or tabular displays. Various levels of displays are provided for growth history data which exhibit a large quantity of information. By selectively choosing the option, users can create the desired level of output display which represents the computed results.

INTERACTIVE-CRKGRO output can be characterized into the following sequential categories:

1. Print the input echo

2. Working spectrum (optional)

3. Computed critical crack length in tabular form for various iterations

4. Computed crack-growth information in tabular form at the desired block intervals

5. Crack-growth summary table which summarizes the preceding growth history

6. Graphical output display of A vs F, da/dF vs F, da/dF vs A, and da/dA vs Kmax/F (optional)

Section IV

EXAMPLE PROBLEM

The following example is selected to demonstrate the capabilities of the program. In order to illustrate the procedure of executing the user-defined stress intensity factor solution option, the example is to predict the growth behavior of a corner crack emanating at a fastener hole contained in a 2219-T851 aluminum plate subjected to transport spectrum loading with each flight containing only the Ground-Air-Ground (G-A-G) cycle as shown in Figure 2. The stress intensity factor solutions for the corner crack at fastener hole developed recently by Newman (5) are employed as the user-defined K-solutions. The angle ϕ was assumed to be equal to 90° in the example. The following is the general stress intensity factor solution for corner crack(s) at a fastener hole as shown in Figure 3, proposed by Newman:

$$K_{I(A)} = \sigma\sqrt{\frac{\pi a}{Q}}\; F_1F_2F_3F_4F_5$$

where $F_1 = \left[M_1 + M_2\,(a/t)^2 + M_3(a/t)^4\right]\, g\, f_\phi$

for $a/c \leq 1$:

$$M_1 = 1.13 - 0.09\,(a/c)$$

$$M_2 = 0.089/(0.2+a/c) - 0.54$$

$$M_3 = 0.5 - 1/(0.65 + a/c) + 14\,(1-a/c)^{24}$$

$$g = 1 + \left[0.1 + 0.35\,(a/t)^2\right]\,(1-\sin\phi)^2$$

$$f_\phi = \left[(a/c)^2\cos^2\phi + \sin^2\phi\right]^{1/4}$$

$$Q = 1 + 1.464\,(a/c)^{1.65}$$

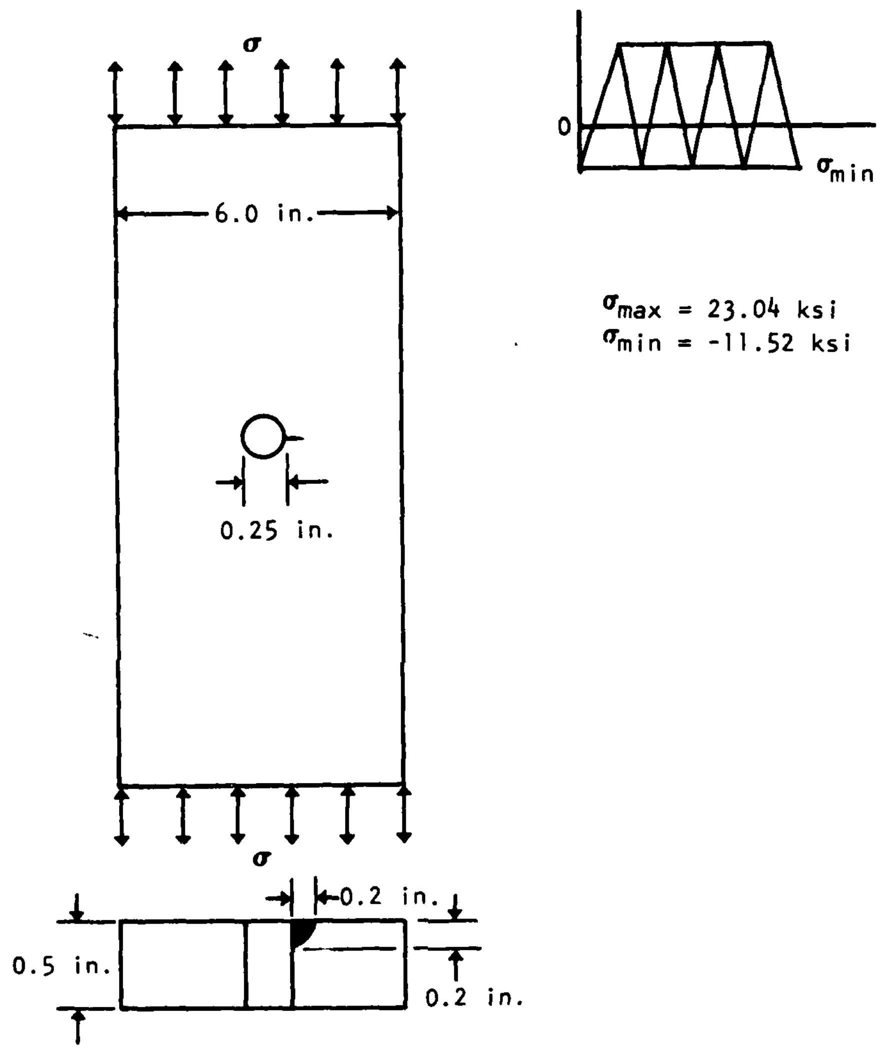
For $a/c > 1$:

$$M_1 = \sqrt{c/a}\,\left[1 + 0.04\,(c/a)\right]$$

$$M_2 = 0.2\,(c/a)^4$$

$$M_3 = -0.11\,(c/a)^4$$

$$g = 1 + \left[0.1 + 0.35\,(c/a)(a/t)^2\right]\,(1 - \sin\phi)^2$$



Material: 2219-T851 aluminum plate

Figure 2. A 2219-T851 Aluminum Plate Containing a Fastener Hole With a Corner Crack Subjected to Transport G-A-G Cycle Loadings

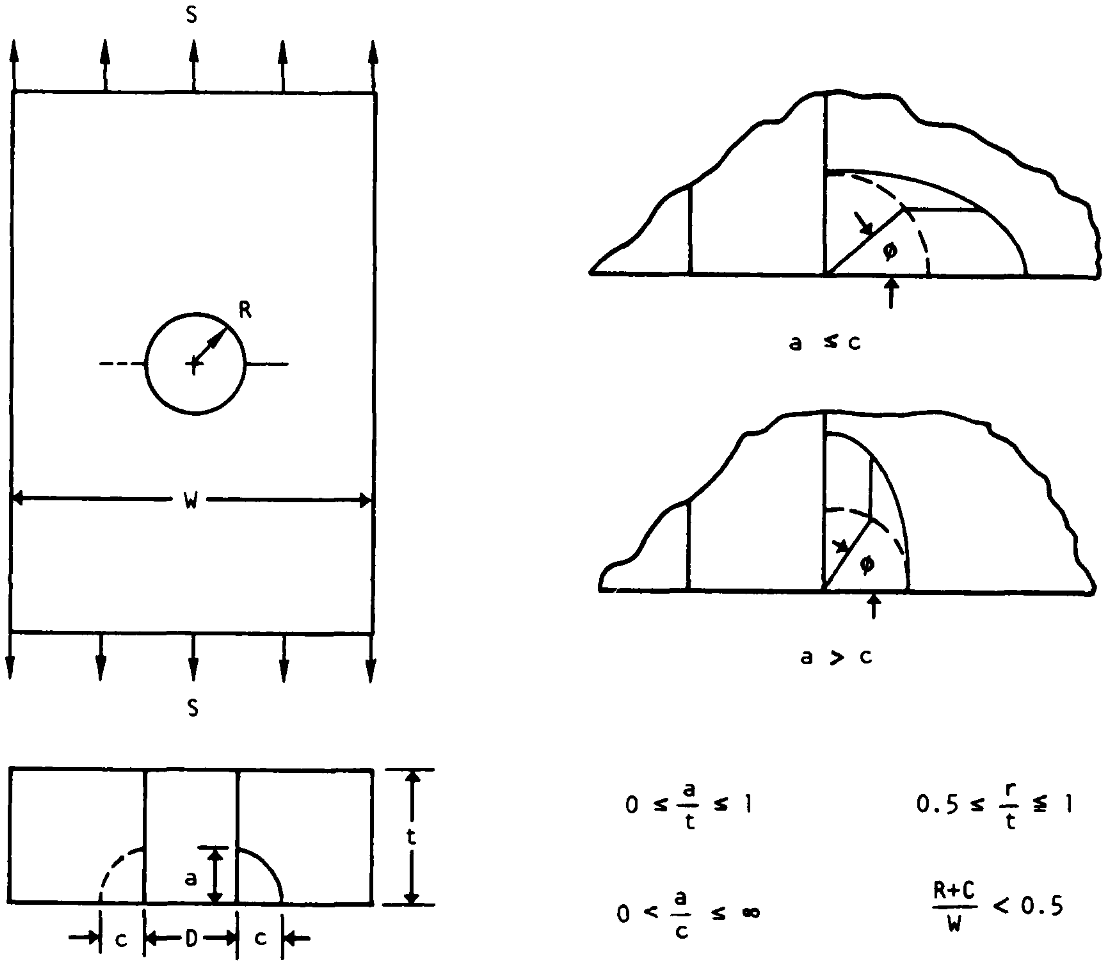


Figure 3. Crack Configuration of a Plate Containing an Open Hole With Corner Crack(s)

$$f\phi = \left[(c/a)^2 \sin^2\phi + \cos^2\phi \right]^{1/4}$$

$$Q = 1 + 1.4.64\ (c/a)^{1.65}$$

$$F_2 = M_4 \left[1 + 0.1(1 - \cos\phi)^2\right] \left[0.8 + 0.2\ (a/t)^{1/4}\right]$$

for a/c $\leq$ 1: $M_4 = 1 + 0.04\ (a/c)$

for a/c > 1: $M_4 = 1.13 - 0.09\ (c/a)$

$$F_3 = \frac{1 - 0.15\lambda + 3.46\lambda^2 - 4.47\lambda^3 + 3.52\lambda^4}{1 + 0.13\lambda^2}$$

$$\lambda = 1/\ (1 + c/r \cos(0.85\phi))$$

$$F_4 = \left[\sec\left(\frac{\pi D}{2W}\right) \sec\left(\frac{\pi}{2}\ \frac{D + bc}{W - 2c + bc}\ \sqrt{a/t}\right)\right]^{1/2}$$

b = 1 for one corner crack

b = 2 for two symmetrical corner cracks

$$F_5 = 1 + (2 - b)\left[\sqrt{\frac{2 + \frac{\pi}{4}\left(\frac{a}{t}\right)\left(\frac{c}{R}\right)}{2 + \frac{\pi}{2}\left(\frac{a}{t}\right)\left(\frac{c}{R}\right)}} - 1\right]$$

Since INTERACTIVE CRKGRO is a two-dimensional crack-growth program for a corner crack, the stress intensity factor solutions at the maximum depth, A, K_{I_A}, and at the maximum length, B, K_{I_B}, are needed to be coded in. The following are the inputs to INTERACTIVE CRKGRO:

```
WELCOME TO CRKGRO INTERACTIVE GRAPHICS PROGRAM VERSION 1.0

ENTER FILE NAME FROM WHICH CRACK GROWTH DATA ARE INPUT
FILE NAME MUST BE FOLLOW BY A '.'
? INPUT.

DO YOU WISH TO ENTER YOUR OWN STRESS INTENSITY FACTOR EQUATION
ENTER 'YES' OR 'NO'
? YES

IS THE STRESS INTENSITY FACTOR EQUATION FOR  PTC  OR  TC
ENTER 'PTC' FOR PART-THROUGH CRACK
      'TC'  FOR THROUGH CRACK
? PTC
```

ENTER YOUR PART-THROUGH CRACK STRESS INTENSITY FACTOR EQUATION

```
1-----7------------*----------*----------*----------*----------*----------*--
      ANGL=PI/2.
      B=1.
      AM1=1.13-0.09*AOC
      AM2=-0.54+0.89/(0.2+AOC)
      AM3=0.5-1./(.65+AOC)+14.*(1.-AOC)**24.
      G=1.+(0.1+.35*AOT**2.)*(1.-SIN(ANGL))**2.
      FANGL=(AOC**2.*COS(ANGL)**2.+SIN(ANGL)**2.)**2.
      Q=1.+1.464*AOC**1.65
      F1=(AM1+AM2*AOT**2.+AM3*AOT**4.)*G*FANGL
      AM4=1.+0.04*AOC
      AM5=1.+0.1*(1.-COS(ANGL))*2.
      AM6=0.8+0.2*AOT**0.25
      F2=AM4*AM5*AM6
      COR=CPL/RADIUS
      D=2.*RADIUS
      W=2.*HALFW
      ALAMDA=1./(1.+COR*COS(.85*ANGL))
      AM7=1.-0.15*ALAMDA+3.46*ALAMDA**2.-4.47*ALAMDA**3.+3.52*ALAMDA**4.

      F3=AM7/(1.+0.13*ALAMDA**2.)
      AM8=1/COS(PI*D/(2.*W))
      AM9=1/COS((PI/2)*((D+B*CPL)/(W-2.*CPL+B*CPL))*SQRT(AOT))
      F4=SQRT(AM8*AM9)
      AM10=2.+PI*AOT*COR/4.
      AM11=2.+PI*AOT*COR/2.
      AM12=SQRT(AM10/AM11)
      F5=1.+(2.-B)*(AM12-1.)
      APREP=SQRT(PI*APL/Q)*F1*F2*F3*F4*F5
      ANGL=0.
      B=1.
      AM1=1.13-0.09*AOC
      AM2=-0.54+0.89/(0.2+AOC)
      AM3=0.5-1./(.65+AOC)+14.*(1.-AOC)**24.


      G=1.+(0.1+.35*AOT**2.)*(1.-SIN(ANGL))**2.
      FANGL=(AOC**2.*COS(ANGL)**2.+SIN(ANGL)**2.)**2.
      Q=1.+1.464*AOC**1.65
      F1=(AM1+AM2*AOT**2.+AM3*AOT**4.)*G*FANGL
      AM4=1.+0.04*AOC
      AM5=1.+0.1*(1.-COS(ANGL))*2.
      AM6=0.8+0.2*AOT**0.25
      F2=AM4*AM5*AM6
      COR=CPL/RADIUS
      D=2.*RADIUS
      W=2.*HALFW
      ALAMDA=1./(1.+COR*COS(.85*ANGL))
      AM7=1.-0.15*ALAMDA+3.46*ALAMDA**2.-4.47*ALAMDA**3.+3.52*ALAMDA**4.
```

```
      F3=AM7/(1.+0.13*ALAMDA**2.)
      AM8=1/COS(PI*D/(2.*W))
      AM9=1/COS((PI/2)*((D+B*CPL)/(W-2.*CPL+B*CPL))*SQRT(AOT))
      F4=SQRT(AM8*AM9)
      AM10=2.+PI*AOT*COR/4.
      AM11=2.+PI*AOT*COR/2.
      AM12=SQRT(AM10/AM11)
      F5=1.+(2.-B)*(AM12-1.)
      CPREP=SQRT(PI*APL/Q)*F1*F2*F3*F4*F5
END
```

Since there is a possibility that the corner crack will grow through the thickness before the K_{1im} reaches its critical value, it is necessary to input the stress intensity factor solution for the through-crack counterpart as follows:

```
ENTER YOUR THROUGH CRACK STRESS INTENSITY FACTOR EQUATION
1-----7------------*----------*----------*----------*----------*
      B=1.
      W=2.*HALFW
      COR=CPL/RADIUS
      E1=1./(1.+COR)
      E2=1.-0.15*E1+3.46*E1**2.-4.47*E1**3.+3.52*E1**4.
      F7=E2/(1+0.13*E1**2.)
      E3=1./COS(PI*RADIUS/W)
      E4=0.5*PI*(2.*RADIUS+B*CPL)/(W-2.*CPL+B*CPL)
      F8=E3*1./COS(E4)
      E5=2.+0.25*PI*COR
      E6=2.+0.5*PI*COR
      E7=SQRT(E5/E6)
      F9=1.+(2.-B)*(E7-1.)
      CPREP=SQRT(PI*CPL)*F7*F8*F9
END
```

To execute the crack-growth analysis portion of the program, the following inputs were coded in:

$C_a = 5.066 \times 10^{-10}$	$C_b = 5.066 \times 10^{-10}$
$n_a = 3.83$	$n_b = 3.83$
$m_a = 0.6$	$m_b = 0.6$
$q_a = 0.3$	$q_b = 0.3$
$K_{c_a} = 45$ ksi $\sqrt{in.}$	$K_{c_b} = 65$ ksi $\sqrt{in.}$
$\sigma_{ty} = 48$ ksi	$R_{so} = 3.0$
$\Delta K_{th_o} = 2.5$ ksi $\sqrt{in.}$	$A = 1$
$R^+_{cut} = 0.75$	$R^-_{cut} = 0.99$

σ_{lim} = 23.04 ksi　　　B = 3.00 in.

t = 0.25 in.　　　R = 0.25 in.

a_i = 0.05 in.　　　C_i = 0.05 in.

σ_{max} = 23.04 ksi　　　σ_{min} = -11.52 ksi

In order to provide a complete picture, hard copies of the computer-prompted statements and the typed-in inputs during the input stage for executing the program to perform this example analysis are presented in the following:

```
 INPUT OPTIONS ARE:
     TITLE      MATERIAL  GEOMETRY  SPECTRUM
     OUTPUT     REPLOT    END DATA  ENDJOB
 YOUR OPTION IS? TITLE
 ENTER TITLE CARD, (MAX OF 70 CHARACTERS)
? NEWMAN'S EQUATION FOR CORNER CRACK FROM HOLE
```

```
 INPUT OPTIONS ARE:
     TITLE     MATERIAL  GEOMETRY  SPECTRUM
     OUTPUT    REPLOT    END DATA  ENDJOB
 YOUR OPTION IS? MATERIAL
 ENTER MATERIAL TITLE CARD, (MAX OF 60 CHARACTERS)
? 2219-T851 ALUMINUM
 ENTER CRACK GROWTH RATE EQUATION CONTROL
   0 - SINGLE SLOPE RATE EQUATION ANALYSIS
   1 - BI-SLOPE RATE EQUATION ANALYSIS
? 1
 ENTER TYPE OF CRACK GROWTH ANALYSIS
   1 - ONE DIMENSION
   2 - TWO DIMENSION
? 2
 ENTER THE DC/DN CRACK GROWTH RATE EQUATION COEFFICIENT FOR REGION I
? 2.126E-13
 ENTER THE DC/DN CRACK GROWTH RATE EQUATION EXPONENT FOR REGION I
? 9.23
 ENTER THE DA/DN CRACK GROWTH RATE EQUATION COEFFICIENT FOR REGION I
? 2.126E-13
 ENTER THE DA/DN CRACK GROWTH RATE EQUATION EXPONENT FOR REGION I
? 9.23
 ENTER THE CRACK GROWTH RATE EQUATION EXPONENTS FOR REGION I
   'M' FOR POSITIVE STRESS RATIO
   ? 0.6
   'Q' FOR NEGATIVE STRESS RATIO
   ? 1.0
```

```
 ENTER THE DC/DN CRACK GROWTH RATE EQUATION COEFFICIENT FOR REGION II
? 5.066E-10
 ENTER THE DC/DN CRACK GROWTH RATE EQUATION EXPONENT FOR REGION II
? 3.83
 ENTER THE DA/DN CRACK GROWTH RATE EQUATION COEFFICIENT FOR REGION II
? 5.066E-10
 ENTER THE DA/DN CRACK GROWTH RATE EQUATION EXPONENT FOR REGION II
? 3.83
 ENTER THE CRACK GROWTH RATE EQUATION EXPONENTS FOR REGION II
    'M' FOR POSITIVE STRESS RATIO
    ? 0.6
    'Q' FOR NEGATIVE STRESS RATIO
    ? 1.0
 ENTER DC/DN VALUE WHERE THE TRANSITION IS TO BE MAKE
? 6.0E-7
 ENTER DELTA K VALUE WHERE THE TRANSITION IS TO BE MAKE
? 5.0
```

```
 ENTER THE FRACTURE TOUGHNESS FOR HALF-CRACK LENGTH DIRECTION, 'C'
? 65.
 ENTER THE FRACTURE TOUGHNESS FOR CRACK DEPTH DIRECTION, 'A'
? 45.
 ENTER THE MATERIAL YIELD STRENGTH
? 48.
 ENTER THE VALUE OF DELTA K THRESHOLD
? 2.5
 ENTER THE THRESHOLD CONSTANT A
? 1.0
 ENTER THE POSITIVE STRESS RATIO CUT-OFF VALUE
? 0.75
 ENTER THE NEGATIVE STRESS RATIO CUT-OFF VALUE
? -0.99
```

```
 INPUT OPTIONS ARE:
     TITLE      MATERIAL   GEOMETRY   SPECTRUM
     OUTPUT     REPLOT     END DATA   ENDJOB
 YOUR OPTION IS? GEOMETRY
 LOAD INTERACTION CONTROL - ENTER 'YES', 'NO', OR 'BOTH'
? YES
 ENTER OVERLOAD SHUT-OFF RATIO
? 3.0
 ENTER CRACK CODE
? 1090
 ENTER THE WIDTH OF THE SPECIMEN
? 6.0
 ENTER THE THICKNESS OF THE SPECIMEN
? 0.25
 ENTER THE RADIUS OF HOLE (IF NO HOLE ENTER 0.0)
? 0.25
 ENTER TRANSITION CODE - (0)  WHEN CRACK EQUALS THICKNESS
                         (1)  BEFORE CRACK EQUALS THICKNESS
? 0
 ENTER THE INITIAL CRACK DEPTH
? 0.05
 ENTER THE FINAL CRACK DEPTH, IF NO FINAL CRACK DEPTH, ENTER 0.0
? 0.0
 ENTER THE INITIAL CRACK LENGTH
? 0.05
 ENTER THE FINAL CRACK LENGTH, IF NO FINAL CRACK LENGTH, ENTER 0.0
? 0.0
```

```
 ENTER THE NUMBER OF LIMIT STRESSES
 (MAXIMUM OF 7)
? 1
 ENTER THE LIMIT STRESSES
? 30.
 CONTROL FOR DETERMINING WHEN INSTABILITY IS REACHED IS
     1 - BY LIMIT STRESS INTENSITY FACTOR
     2 - BY MAXIMUM STRESS INTERSITY FACTOR
? 2
```

```
 INPUT OPTIONS ARE:
     TITLE     MATERIAL  GEOMETRY  SPECTRUM
     OUTPUT    REPLOT    END DATA  ENDJOB
 YOUR OPTION IS? SPECTRUM
 ENTER THE SPECTRUM TITLE, (MAXIMUM OF 70 CHARACTERS)
? FIGHTER AIR-TO-GROUND SPECTRUM
 ENTER SPECTRUM SCALER FACTOR
? 0.3
 ENTER RANGE RAIR COUNTING CONTROL
   0 - NO RANGE PAIR COUNTING
   1 - RANGE PAIR COUNTING
? 1
 ENTER UNIT NUMBER FOR INPUT OF SPECTRUM
? 5
 THE FLIGHT SPECTRUM SEGMENT TYPES ARE:
     MAX-MIN   R-DELTA   MEAN      END
 ENTER SEGMENT TYPE
? MAX-MIN
```

```
 ENTER THE FLIGHT SEGMENT DESCRIPTION, (MAXIMUM OF 70 CHARACTERS)
? AIR-TO-GROUND MISSION

 THE INPUT SPECTRUM TERMS MUST BE SEPARATED BY A COMMA
 I.E. (100. , 0. , 1.)
? 50.1, 29.6, 1.
? 41.9,  4.2, 1.
? 20.1,  7.8, 1.
? 48.9,  6.3, 1.
? 37.1,  8.4, 1.
? 37.8, 16.4, 1.
? 28.6, 17.8, 1.
? 49.5, 13.8, 1.
? 26.9,  4.0, 1.
? 42.9, 11.4, 1.
? 74.1, 20.3, 1.
? 34.5,  1.5, 1.
? 21.0,  7.8, 1.
? 39.5, 11.9, 1.
? 23.8,  2.1, 1.
? 71.5, 11.3, 1.
? 43.8,  8.5, 1.
? 33.1, 10.9, 1.
? 56.3,-10.0, 1.
? 51.4,  0.6, 1.
? 18.9,  7.0, 1.
? 55.9, 31.7, 1.
? 48.6,  3.0, 1.
? 17.3,  6.9, 1.
? 44.1, 30.6, 1.
? 42.4, 25.3, 1.
? 44.3,  2.9, 1.
? 31.2,  4.9, 1.
```

```
? 28.6,  8.6, 1.
? 29.7, 18.0, 1.
? 28.4, 14.4, 1.
? 44.3, 16.4, 1.
? 35.2,  8.0, 1.
? 51.8,  8.1, 1.
? 23.3,  2.8, 1.
? 21.7,  8.7, 1.
? 59.5, 12.3, 1.
? 47.3,-10.0, 1.
? 67.1, 42.2, 1.
? 57.2, 14.5, 1.
? 35.4, 11.8, 1.
? 27.8,  5.5, 1.
? 19.6,  3.7, 1.
? 27.7,  8.9, 1.
? 31.1,  0.6, 1.
? 28.8,  9.2, 1.
? 22.6, 12.5, 1.
? 41.6,  0.5, 1.
? 26.4, 10.3, 1.
? 39.3, -0.1, 1.
? 19.5,  5.1, 1.
? 28.7,  5.7, 1.
? 31.4,  4.3, 1.
? 22.3, 10.7, 1.
? 24.5,  1.6, 1.
? 12.0,  0.0, 1.
? 48.2,-10.0, 1.
? END
```

```
 THE FLIGHT SPECTRUM SEGMENT TYPES ARE:
     MAX-MIN   R-DELTA   MEAN      END
 ENTER SEGMENT TYPE
? END
 ENTER THE MISSION MIX DEFINITION
? MISSION=1500
 ENTER THE NUMBER OF FLIGHTS PER BLOCK
? 3
```

```
 INPUT OPTIONS ARE:
     TITLE      MATERIAL  GEOMETRY  SPECTRUM
     OUTPUT     REPLOT    END DATA  ENDJOB
 YOUR OPTION IS? OUTPUT
 IS THE SPECTRUM TO BE PRINTED, 'YES' OR 'NO'
? YES
 PRINT CRACK GROWTH HISTORY DATA IN INCRETEMENTS OF -- BLOCKS
? 250
 IS PLOTTING TO BE DONE, 'YES' OR 'NO'
? YES
```

```
 SPECIFY THE TYPE OF PLOTS YOU WOULD LIKE
 A      VS. F
? YES
 DA/DF VS. F
? YES
 DA/DF VS. A
? YES
 DA/DF VS. KMAX/FLT
? YES
 SPECIFY THE TYPE OF GRID DESIRED
 FOR X-AXIS, ENTER 0 - LINEAR OR 1 - LOG
? 0
 FOR Y-AXIS, ENTER 0 - LINEAR OR 1 - LOG
? 0
 FOR X-AXIS, ENTER 0 - LINEAR OR 1 - LOG
? 0
 FOR Y-AXIS, ENTER 0 - LINEAR OR 1 - LOG
? 1
 FOR X-AXIS, ENTER 0 - LINEAR OR 1 - LOG
? 0
 FOR Y-AXIS, ENTER 0 - LINEAR OR 1 - LOG
? 1
 FOR X-AXIS, ENTER 0 - LINEAR OR 1 - LOG
? 1
 FOR Y-AXIS, ENTER 0 - LINEAR OR 1 - LOG
? 1
```

```
 SHALL THE SLOW GROWTH RATE STEPS BE BYPASSED, 'YES' OR 'NO'
? NO
 SHALL THE STRESS INTENSITY EQUATIONS BE PRINTED, 'YES' OR 'NO'
? NO
 SHALL THE 1ST BLOCK'S GROWTH DATA BE PRINTED, 'YES' OR 'NO'
? YES
 ENTER THE NUMBER OF STEPS TO BE PRINTED IN THE REQUESTED PRINT BLOCK
? -15
```

```
 INPUT OPTIONS ARE:
     TITLE     MATERIAL  GEOMETRY  SPECTRUM
     OUTPUT    REPLOT    END DATA  ENDJOB
 YOUR OPTION IS? END DATA
 WHEN A '?' IS PRINTED ON THE SCREEN, ENTER A 'P' AND PRESS RETURN
 TO START PRINTING, OR TO CONTINUE PRINTING
? P
```

The outputs of the analysis are shown on the following pages. The outputs start with the input-echo and the estimation of the critical crack length. Printouts of the detailed calculation in block 1, and so on, then followed. A summary table of the crack growth for every block (21 cycles) is shown as the last tabulated output. For illustration, the CRT plots of crack length versus number of flights is also presented. Since one flight only contains one G-A-G cycle, the total number of flights and the total number of cycles are identical.

```
                    C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

CRACK CODE:  1090 --- USER'S OWN PTC SIF EQUATION
LOAD INTERACTION:  WILLENBORG-CHANG
DAMAGE ACCUMULATION:    VROMAN (LINEAR APPRX.)
CRACK GROWTH RATE EQ.:  MODIFIED WALKER
ANALYSIS IS PREFORMED WITH A SPECTRUM THAT HAS BEEN RANGED PAIRED
INSTABILITY WILL BE BASED ON MAXIMUM STRESS

MATERIAL:  2219-T851 ALUMINUM
                              DEPTH          LENGTH
                            DIRECTION       DIRECTION
FRACTURE TOUGHNESS            45.000          65.000
GROWTH RATE EQ. CONST. C    5.0660E-10      5.0660E-10
GROWTH RATE EQ. EXP.   N       3.830           3.830
GROWTH RATE EQ. EXP. M =        .600
GROWTH RATE EX. EXP. Q =       1.000

YIELD STRENGTH =               48.000 KSI.
DELTH KTH = (1 - 1.0 * ABS(R)) *   2.500
+R CUT-OFF =  .750
-R CUT-OFF = -.990
OVERLOAD SHUT-OFF RATIO = 3.000
HALF PLATE WIDTH (B) =  3.000 IN.
PLATE THICKNESS  (T) =   .250 IN.
RADIUS OF HOLE   (R) =   .250 IN.
INITIAL HALF CRACK LENGTH (C) =    .050 IN.
INITIAL CRACK DEPTH (A) =    .050 IN.
A/C RATIO =   1.000
?
```

```
                  C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

YIELD STRENGTH =                48.000 KSI.
DELTH KTH = (1 - 1.0 * ABS(R)) *   2.500
+R CUT-OFF =  .750
-R CUT-OFF = -.990
OVERLOAD SHUT-OFF RATIO = 3.000
HALF PLATE WIDTH (B) =  3.000 IN.
PLATE THICKNESS  (T) =   .250 IN.
RADIUS OF HOLE   (R) =   .250 IN.
INITIAL HALF CRACK LENGTH (C) =    .050 IN.
INITIAL CRACK DEPTH (A) =    .050 IN.
A/C RATIO =   1.000
?
```

DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

M I S S I O N M I X

MAXIMUM NUMBER OF LOAD BLOCKS = 1500
THE LOADING SPECTRUM HAS 1 MISSION(S)
DESIGN LIMIT STRESS = 30.000 (KSI)

FIGHTER AIR-TO-GROUND SPECTRUM

*** SPECTRUM HAS BEEN RANGE-PAIRED ***

SPECTRUM FOR SEGMENT 1
AIR-TO-GROUND MISSION

STEP NO	MAX. STRESS	MIN. STRESS	CYCLES
1	15.030	1.200	1.000
2	12.570	8.880	1.000
3	6.030	2.340	1.000
4	14.670	1.890	1.000
5	11.130	2.520	1.000
6	11.340	4.920	1.000
7	8.580	5.340	1.000
8	14.850	1.260	1.000
9	8.070	4.140	1.000
10	12.870	3.420	1.000
11	22.230	-3.000	1.000
12	10.350	6.090	1.000
13	6.300	2.340	1.000
14	11.850	.630	1.000
15	7.140	3.570	1.000
16	21.450	.450	1.000
17	13.080	3.390	1.000

?

C R K G R O
DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

STEP NO	MAX. STRESS	MIN. STRESS	CYCLES
18	9.930	3.270	1.000
19	16.890	2.550	1.000
20	15.420	.180	1.000
21	5.670	2.100	1.000
22	16.770	.840	1.000
23	14.580	9.510	1.000
24	5.190	2.070	1.000
25	13.230	7.590	1.000
26	12.720	9.180	1.000
27	13.290	.900	1.000
28	9.360	1.470	1.000
29	8.580	2.580	1.000
30	8.910	4.320	1.000
31	8.520	5.400	1.000
32	13.290	2.400	1.000
33	10.560	4.920	1.000
34	15.540	.870	1.000
35	6.990	2.430	1.000
36	6.510	2.610	1.000
37	17.850	-3.000	1.000
38	14.190	3.690	1.000
39	20.130	-3.000	1.000
40	17.160	12.660	1.000
41	10.620	4.350	1.000
42	8.340	3.540	1.000
43	5.880	1.650	1.000
44	8.310	2.670	1.000
45	9.330	1.110	1.000
46	8.640	2.760	1.000
47	6.780	3.750	1.000

?

```
                             C R K G R O                          01/19/82   PAGE  20
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

STEP NO       MAX. STRESS       MIN. STRESS      CYCLES
  48               12.480              .180       1.000
  49                7.920             3.090       1.000
  50               11.790              .150       1.000
  51                5.850             1.530       1.000
  52                8.610             1.710       1.000
  53                9.420             0.000       1.000
  54                6.690             3.210       1.000
  55                7.350             1.290       1.000
  56                3.600              .480       1.000
  57               14.460             -.030       1.000

**********  END OF INPUT  **********
?
```

C R K G R O
DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

ESTIMATION OF THE CRITICAL CRACK LENGTH
BASED ON KLIMIT AND CONSTANT ASPECT RATIO

ITERATION	CRACK SIZE	STRESS INTENSITY (LIMIT)	STRESS INTENSITY CORRECTION FACTOR
1	.050	25.156	3.321
2	.250	45.424	2.682
3	.150	39.463	3.008
4	.200	43.239	2.854
5	.225	44.542	2.772
6	.238	45.039	2.728

APPROXIMATE CRITICAL CRACK (A OR C) = .238 IN.
WHEN K-LIMIT IS WITHIN A 0.5% TOLERANCE OF K CRITICAL
?

C R K G R O
DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK 1 A = 5.0000E-02
C = 5.0000E-02

STEP	CYCLES	A C	A/2C A/T	DA/DN DC/DN	DELTAK DELTCK	KMAX-A KMAX-C	SIGMAX-A SIGMAX-C (EFF)	R-A R-C (EFF)
1	1.0	.050	.500	6.9224E-06	11.6	12.6	15.030	.1
		.050	.201	2.2485E-06	8.7	9.4	15.030	.1
2	1.0	.050	.500	5.0829E-07	3.1	9.8	11.637	.7
		.050	.201	3.3938E-08	2.3	7.4	11.733	.7
3	1.0	.050	.500	7.7984E-09	3.1	3.2	3.754	.2
		.050	.201	5.2087E-10	2.3	2.8	4.508	.2
4	1.0	.050	.500	5.4841E-06	10.7	12.2	14.533	.1
		.050	.201	1.7859E-06	8.0	9.1	14.542	.1
5	1.0	.050	.500	1.1933E-06	7.2	8.2	9.711	.1
		.050	.201	3.9926E-07	5.4	6.2	9.884	.1
6	1.0	.050	.500	6.3482E-07	5.4	8.4	9.990	.4
		.050	.201	4.1650E-07	4.0	6.4	10.149	.4
7	1.0	.050	.500	2.8542E-08	2.7	5.4	6.483	.5
		.050	.201	1.9130E-09	2.0	4.3	6.858	.5
8	1.0	.050	.500	6.4888E-06	11.4	12.4	14.790	.1
		.050	.201	2.1141E-06	8.5	9.3	14.791	.1
9	1.0	.050	.500	5.8234E-08	3.3	4.9	5.887	.3
		.050	.201	3.9155E-09	2.5	4.0	6.315	.4
10	1.0	.050	.500	2.0589E-06	7.9	10.1	12.057	.2
		.050	.201	6.7824E-07	5.9	7.6	12.134	.2
11	1.0	.050	.500	4.0221E-05	21.2	18.7	22.230	-.1
		.050	.201	1.3127E-05	15.8	13.9	22.230	-.1

C R K G R O

DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK 1 A = 5.0000E-02
C = 5.0000E-02

STEP	CYCLES	A C	A/2C A/T	DA/DN DC/DN	DELTAK DELTCK	KMAX-A KMAX-C	SIGMAX-A SIGMAX-C (EFF)	R-A R-C (EFF)
12	1.0	.050	.500	1.4634E-07	3.6	5.6	6.693	.4
		.050	.201	1.0047E-08	2.7	4.5	7.188	.4
13	1.0	.050	.500	0.	3.3	2.1	2.522	-.6
		.050	.201	0.	2.5	2.3	3.659	-.1
14	1.0	.050	.500	1.3834E-06	9.4	7.2	8.568	-.3
		.050	.201	4.8012E-07	7.1	5.6	8.937	-.3
15	1.0	.050	.500	2.2740E-09	3.0	2.7	3.210	-.1
		.050	.201	2.5078E-10	2.2	2.6	4.154	.1

THE CRACK AT THE END OF BLOCK 1 HAS C = 5.0062E-02
A = 5.0185E-02

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                      C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK   157    A = 9.1007E-02
                                              C = 8.4007E-02

 STEP  CYCLES     A       A/2C    DA/DN     DELTAK  KMAX-A  SIGMAX-A   R-A
                  C       A/T     DC/DN     DELTCK  KMAX-C  SIGMAX-C   R-C
                                                               (EFF) (EFF)

***********************************************************************
AT FRACTIONAL (.7,.8, OR .9) K1C OF  31.500
KLIMIT=  31.505     A=9.1215E-02     C=8.4196E-02
IN BLOCK   157     STEP    18  CYCLE     0.0
***********************************************************************
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                 C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK   228    A = 1.2892E-01
                                             C = 1.1859E-01

 STEP  CYCLES     A       A/2C   DA/DN     DELTAK  KMAX-A  SIGMAX-A   R-A
                  C       A/T    DC/DN     DELTCK  KMAX-C  SIGMAX-C   R-C
                                                              (EFF) (EFF)

***********************************************************************
AT FRACTIONAL (.7,.8, OR .9) K1C OF  36.000
KLIMIT=  36.014     A=1.2914E-01     C=1.1879E-01
IN BLOCK   228     STEP    13  CYCLE     0.0
***********************************************************************
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C R K G R O
DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK 250 A = 1.4530E-01
C = 1.3377E-01

STEP	CYCLES	A / C	A/2C / A/T	DA/DN / DC/DN	DELTAK / DELTCK	KMAX-A / KMAX-C	SIGMAX-A / SIGMAX-C (EFF)	R- / R- (EFF
1	1.0	.145	.543	1.9540E-05	17.3	15.6	12.414	-.
		.134	.584	1.7890E-05	17.0	15.2	12.317	-.
2	1.0	.145	.543	6.9980E-07	4.6	11.3	9.004	.
		.134	.584	6.4486E-07	4.5	11.0	8.910	.
3	1.0	.145	.543	0.	4.6	1.3	1.006	-1.
		.134	.584	0.	4.5	1.2	.966	-1.
4	1.0	.145	.543	1.6216E-05	16.0	14.9	11.915	-.
		.134	.584	1.4778E-05	15.7	14.6	11.814	-.
5	1.0	.145	.543	2.5681E-06	10.8	8.9	7.065	-.
		.134	.584	2.3497E-06	10.6	8.6	6.975	-.
6	1.0	.145	.543	1.8294E-06	8.0	9.2	7.346	.
		.134	.584	1.6805E-06	7.9	8.9	7.254	.
7	1.0	.145	.543	1.5860E-07	4.1	4.8	3.801	.
		.134	.584	1.3537E-07	4.0	4.6	3.727	.
8	1.0	.145	.543	1.8172E-05	17.0	15.3	12.174	-.
		.134	.584	1.6608E-05	16.7	14.9	12.069	-.
9	1.0	.145	.543	1.2456E-07	4.9	4.0	3.196	-.
		.134	.584	8.5992E-08	4.8	3.8	3.123	-.
10	1.0	.145	.543	6.4826E-06	11.8	11.8	9.427	-.
		.134	.584	5.8268E-06	11.6	11.5	9.325	-.
11	1.0	.146	.543	1.8567E-04	31.6	27.9	22.230	-.
		.134	.584	1.7388E-04	31.1	27.4	22.230	-.

C R K G R O
DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK 250 A = 1.4530E-01
C = 1.3377E-01

STEP	CYCLES	A C	A/2C A/T	DA/DN DC/DN	DELTAK DELTCK	KMAX-A KMAX-C	SIGMAX-A SIGMAX-C (EFF)	R-A R-C (EFF)
12	1.0	.146	.543	5.5578E-07	5.3	7.8	6.236	.3
		.134	.585	5.1834E-07	5.2	7.7	6.219	.3
13	1.0	.146	.543	0.	5.0	1.8	1.433	-1.0
		.134	.585	0.	4.9	1.8	1.444	-1.0
14	1.0	.146	.543	6.2095E-06	14.1	10.3	8.236	-.4
		.134	.585	5.8079E-06	13.8	10.1	8.213	-.4
15	1.0	.146	.543	4.2922E-08	4.5	2.9	2.313	-.5
		.134	.585	3.6786E-08	4.4	2.9	2.314	-.5

THE CRACK AT THE END OF BLOCK 250 HAS C = 1.3452E-01
A = 1.4612E-01

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                 C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK   287    A = 1.7983E-01
                                             C = 1.6640E-01

 STEP  CYCLES    A      A/2C   DA/DN     DELTAK  KMAX-A  SIGMAX-A   R-A
                 C      A/T    DC/DN     DELTCK  KMAX-C  SIGMAX-C   R-C
                                                            (EFF) (EFF)

************************************************************************
AT FRACTIONAL (.7,.8, OR .9) K1C OF  40.500
KLIMIT=  40.508     A=1.8084E-01     C=1.6737E-01
IN BLOCK   287     STEP    41  CYCLE     0.0
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                       C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

************************************************************************
BREAKTHROUGH HAS OCCURRED AT A=2.5001E-01,  C=2.3632E-01
AT      1.0 CYCLES OF STEP     8 IN BLOCK   341
************************************************************************
?
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C R K G R O

DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK 500 C = 3.3127E-01

STEP	CYCLES	C	DC/DN	DELTCK	KMAX-C	SIGMAX	R	SIGMAX (EFF)	R (EFF)
1	1.0	.331	1.5947E-05	16.5	14.7	15.030	.1	12.316	-.1
2	1.0	.331	5.7557E-07	4.4	10.7	12.570	.7	8.918	.6
3	1.0	.331	0.	4.4	1.2	6.030	.4	1.033	-1.0
4	1.0	.331	1.3172E-05	15.3	14.1	14.670	.1	11.814	-.1
5	1.0	.331	2.1016E-06	10.3	8.4	11.130	.2	6.989	-.2
6	1.0	.331	1.5018E-06	7.7	8.7	11.340	.4	7.268	.1
7	1.0	.331	9.8506E-08	3.9	4.5	8.580	.6	3.760	.1
8	1.0	.331	1.4796E-05	16.2	14.4	14.850	.1	12.068	-.1
9	1.0	.331	7.6954E-08	4.7	3.8	8.070	.5	3.161	-.2
10	1.0	.331	5.2031E-06	11.3	11.2	12.870	.3	9.330	-.0
11	1.0	.331	1.5491E-04	30.2	26.6	22.230	-.1	22.230	-.1
12	1.0	.331	4.6422E-07	5.1	7.5	10.350	.6	6.246	.3
13	1.0	.331	0.	4.7	1.8	6.300	.4	1.512	-1.0
14	1.0	.331	5.1724E-06	13.4	9.8	11.850	.1	8.233	-.4
15	1.0	.331	2.6108E-08	4.3	2.8	7.140	.5	2.369	-.5

THE CRACK AT THE END OF BLOCK 500 HAS C = 3.3194E-01

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                  C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK   932    C = 7.7824E-01

 STEP CYCLES   C     DC/DN    DELTCK KMAX-C  SIGMAX   R    SIGMAX   R
                                                           (EFF) (EFF)

***********************************************************************
AT FRACTIONAL (.7,.8, OR .9) KIC OF  45.500
KLIMIT=  45.500     C=7.7876E-01
IN BLOCK   932     STEP    12  CYCLE     0.0
***********************************************************************
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                    C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK  1053    C = 1.0346E+00

 STEP CYCLES   C     DC/DN    DELTCK KMAX-C  SIGMAX   R    SIGMAX   R
                                                        (EFF) (EFF)

***********************************************************************
AT FRACTIONAL (.7,.8, OR .9) KIC OF  52.000
KLIMIT=  52.003     C=1.0367E+00
IN BLOCK  1053     STEP    39  CYCLE     0.0
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                    C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK  1115    C = 1.2462E+00

 STEP CYCLES   C      DC/DN    DELTCK KMAX-C  SIGMAX   R    SIGMAX   R
                                                             (EFF) (EFF)

***********************************************************************
AT FRACTIONAL (.7,.8, OR .9) KIC OF  58.500
KLIMIT=  58.508     C=1.2503E+00
IN BLOCK  1115     STEP    41  CYCLE     0.0
***********************************************************************
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                    C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK  1148    C = 1.4183E+00

 STEP CYCLES   C     DC/DN    DELTCK KMAX-C  SIGMAX   R    SIGMAX   R
                                                        (EFF) (EFF)


************************************************************************
KLIMIT =    65.036 IS GREATER THAN KSUBC =    65.000
VALUES BEFORE INSTABILITY WERE
STEP     40 CYCLE       0.0 OF BLOCK   1148 WITH C = 1.4243E+00
************************************************************************
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                    C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

THE CRACK AT THE BEGINNING OF BLOCK  1186    C = 1.8180E+00

 STEP CYCLES    C      DC/DN    DELTCK KMAX-C  SIGMAX   R    SIGMAX   R
                                                              (EFF) (EFF)


************************************************************************
**** INSTABILITY OCCURRED BY APPLIED KMAX, NOT KLIMIT ****
KMAX =    65.147 IS GREATER THAN KSUBC =    65.000
VALUES BEFORE INSTABILITY WERE
STEP     11 CYCLE       0.0 OF BLOCK   1186 WITH C = 1.8197E+00
************************************************************************
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C R K G R O
DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE

ANALYSIS IS DONE WITH LOAD INTERACTION.

CRACK GROWTH SUMMARY TABLE FOR EVERY 8 BLOCKS

INITIAL CRACK DEPTH WAS A= .050 IN.
INITIAL CRACK LENGTH WAS C= .050 IN.

A	.051	.053	.054	.056	.057	.059	.061
C	.051	.051	.052	.053	.054	.056	.057
A	.063	.065	.066	.069	.071	.073	.075
C	.059	.060	.062	.064	.066	.068	.070
A	.078	.081	.083	.086	.089	.093	.096
C	.072	.075	.077	.080	.083	.086	.089
A	.100	.104	.108	.112	.117	.122	.127
C	.092	.096	.099	.103	.107	.112	.117
A	.132	.138	.144	.151	.158	.166	.174
C	.122	.127	.133	.139	.146	.153	.160
A	.182	.191	.200	.210	.221	.232	.244
C	.168	.177	.186	.196	.207	.218	.230
A							
C	.238	.243	.247	.251	.256	.260	.265
A							

C R K G R O

DETAILED FATIGUE CRACK GROWTH ANALYSIS PROGRAM

C	.270	.274	.279	.284	.288	.293	.298
A C	.303	.308	.314	.319	.324	.329	.335
A C	.340	.346	.351	.357	.363	.368	.374
A C	.380	.386	.392	.399	.405	.411	.418
A C	.424	.431	.438	.444	.451	.458	.466
A C	.473	.480	.488	.495	.503	.511	.519
A C	.527	.535	.543	.552	.560	.569	.578
A C	.587	.596	.606	.615	.625	.635	.645
A C	.656	.666	.677	.688	.700	.711	.723
A C	.735	.748	.760	.773	.787	.800	.814
A C	.829	.844	.859	.875	.891	.908	.926

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                       C R K G R O
DETAILED  FATIGUE  CRACK  GROWTH  ANALYSIS  PROGRAM
A
C       .944      .963      .982     1.002     1.024     1.046     1.069

A
C      1.093     1.119     1.146     1.174     1.205     1.238     1.273

A
C      1.311     1.353     1.399     1.452     1.512     1.584     1.674

A
C      1.798

THE CRITICAL CRACK IS: C= 1.8197E+00
IN BLOCK   1186 STEP     11 CYCLE     0.0

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?
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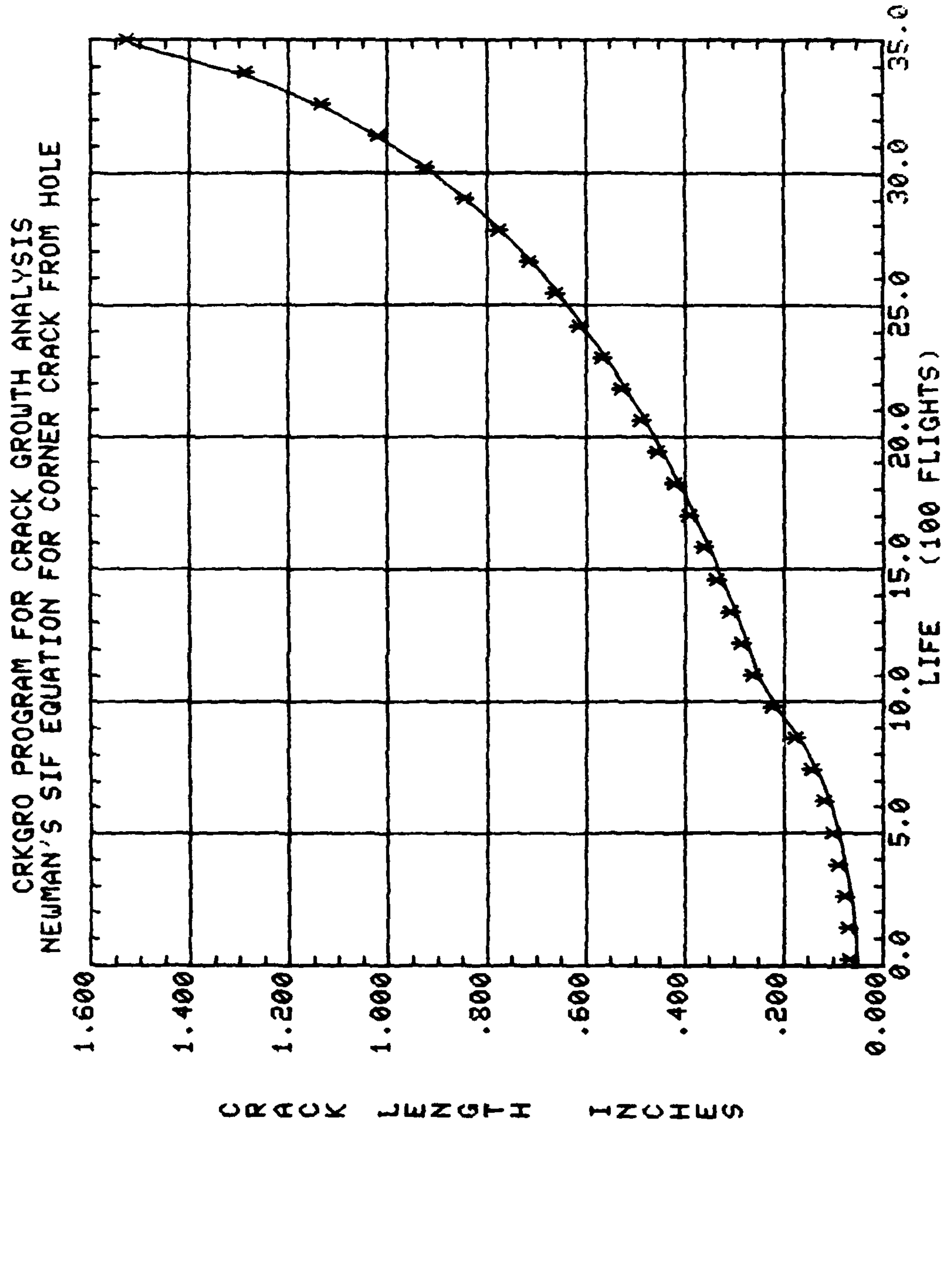
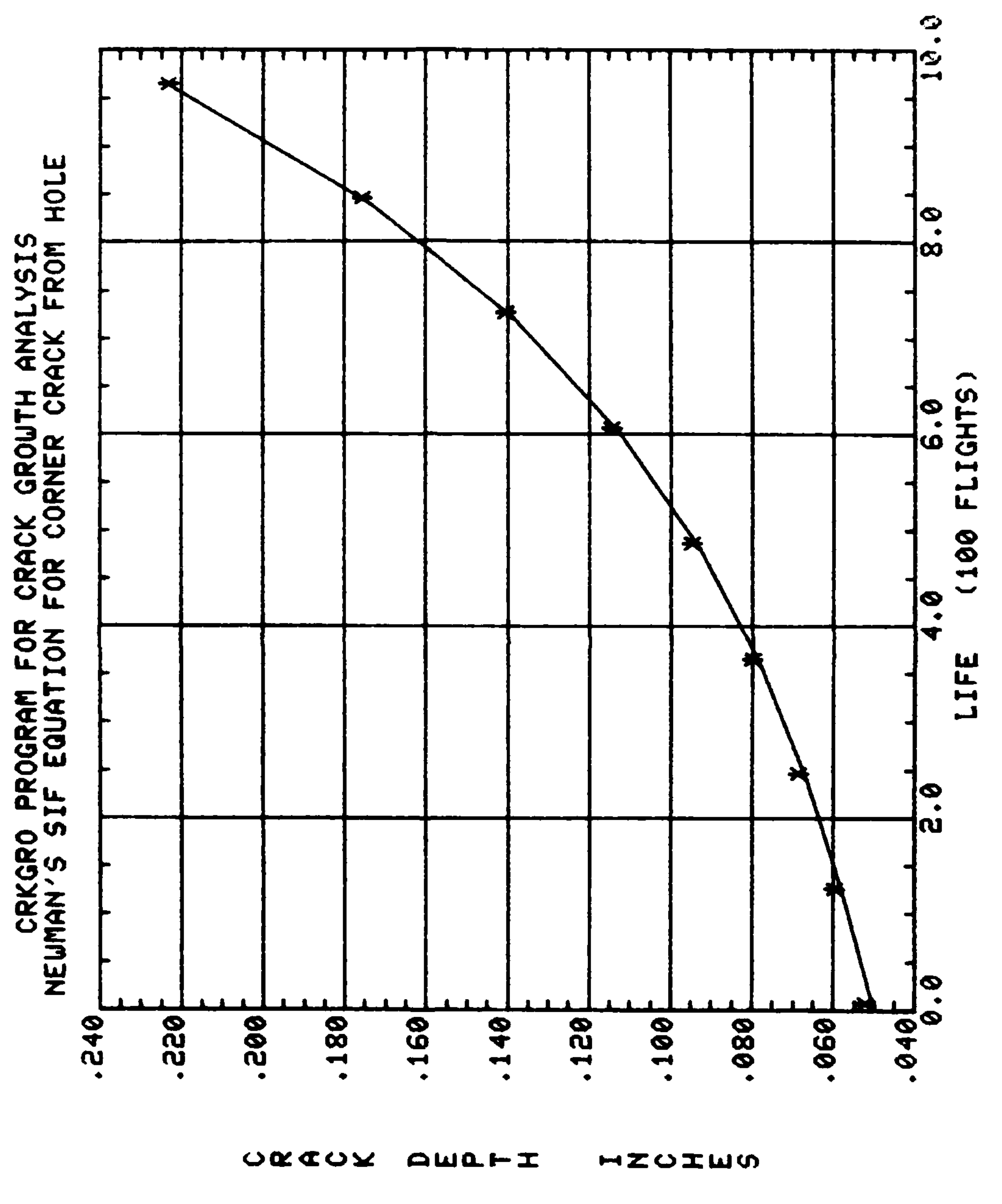
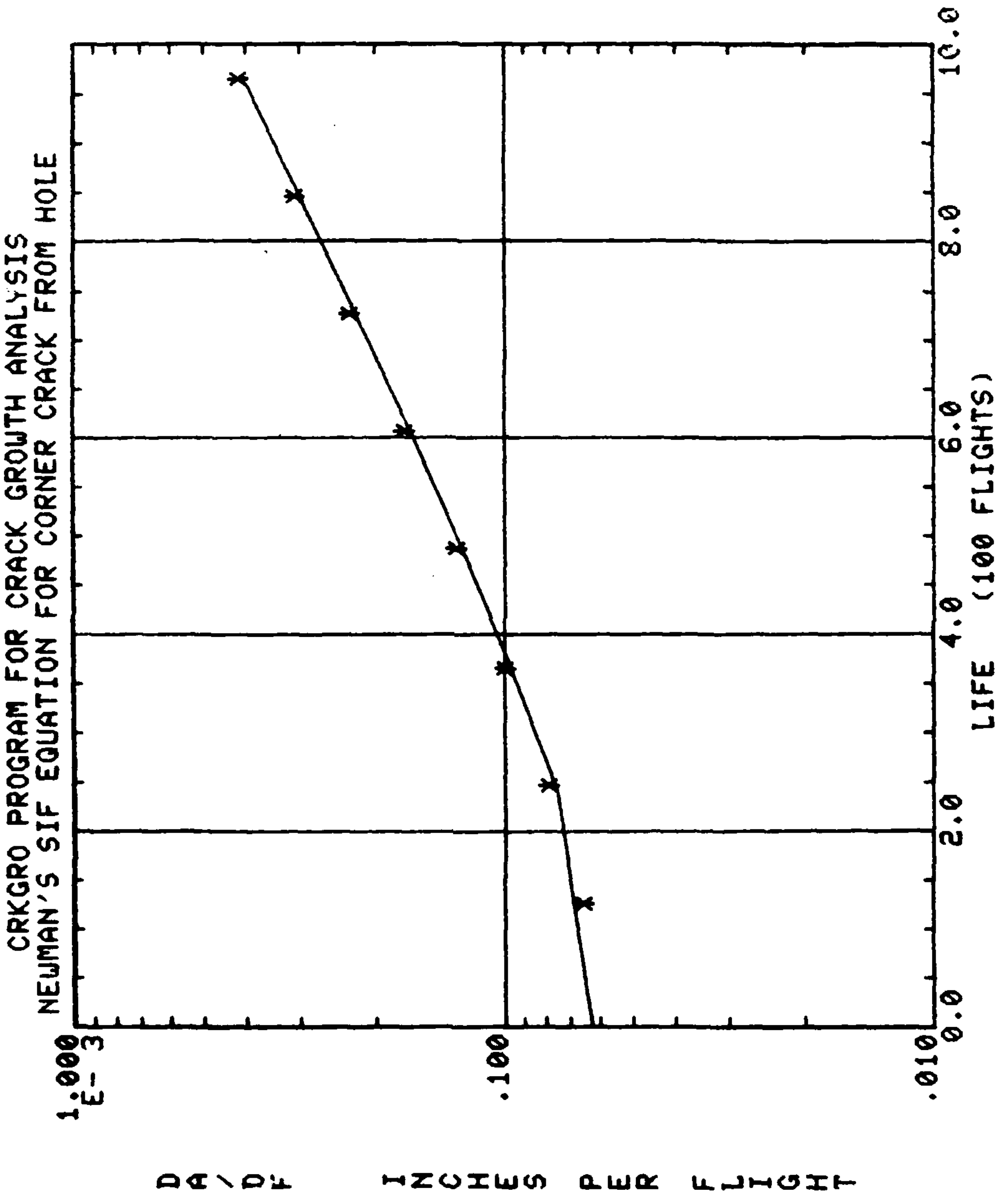
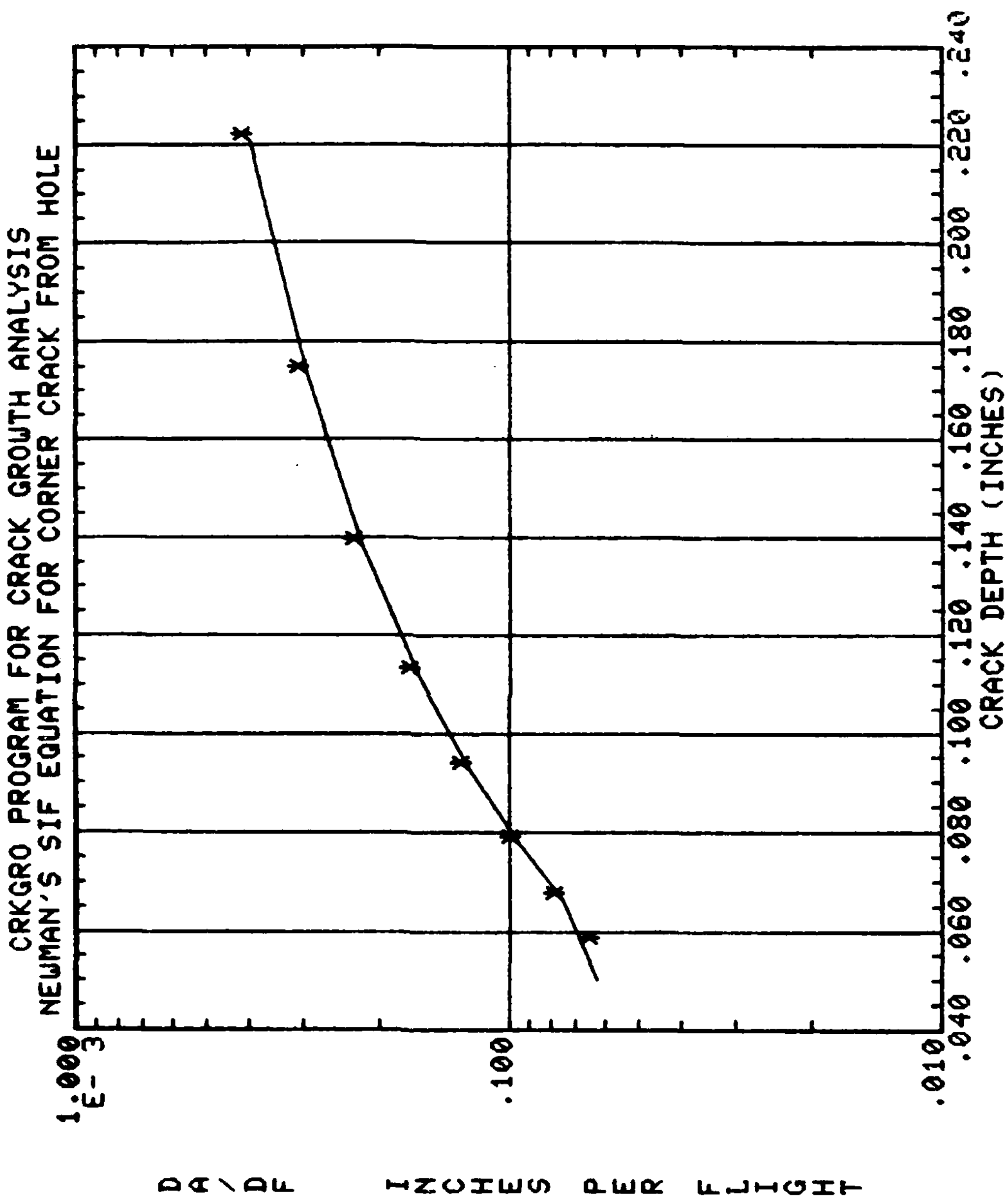
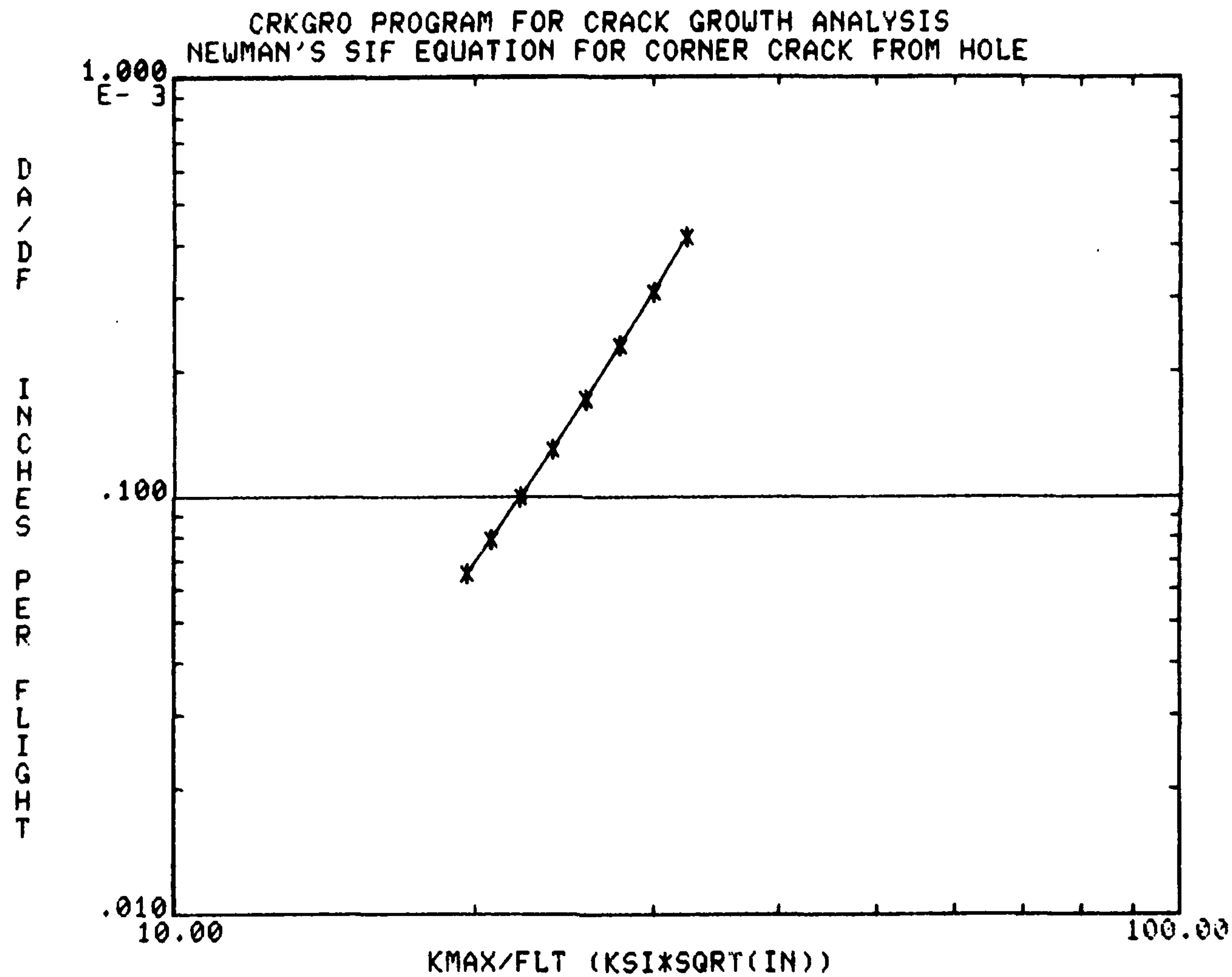

CRKGRO PROGRAM FOR CRACK GROWTH ANALYSIS
NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE
CRACK LENGTH INCHES
1.600
1.400
1.200
1.000
.800
.600
.400
.200
0.000
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
LIFE (100 FLIGHTS)


CRKGRO PROGRAM FOR CRACK GROWTH ANALYSIS
NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE
CRACK DEPTH INCHES
LIFE (100 FLIGHTS)
.240
.220
.200
.180
.160
.140
.120
.100
.080
.060
.040
0.0
2.0
4.0
6.0
8.0
10.0


CRKGRO PROGRAM FOR CRACK GROWTH ANALYSIS
NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE
1.000
E- 3
.100
.010
0.0
2.0
4.0
6.0
8.0
10.0
LIFE (100 FLIGHTS)
DA/DF INCHES PER FLIGHT



CRKGRO PROGRAM FOR CRACK GROWTH ANALYSIS
NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE
1.000
E-3
.100
.010
DA/DF INCHES PER FLIGHT
.040 .060 .080 .100 .120 .140 .160 .180 .200 .220 .240
CRACK DEPTH (INCHES)


CRKGRO PROGRAM FOR CRACK GROWTH ANALYSIS
NEWMAN'S SIF EQUATION FOR CORNER CRACK FROM HOLE
1.000
E- 3
.100
.010
10.00
100.00
DA/DF INCHES PER FLIGHT
KMAX/FLT (KSI*SQRT(IN))

REFERENCES

1. Anon, "INTERCOM Version 4 Reference Manual," Control Data Corporation publication 60494600, Control Data Corporation, Publication and Graphics Division, St. Paul, Minneapolis 55112, 1976

2. Chang, J. B., and Szamossi, M., "A User's Manual for a Detailed Level Level Fatigue Crack Growth Analysis Computer Code, Volume 1, the CRKGRO program," AFWAL-TR-81-3093, Vol. I, Air Force Wright-Patterson Air Force Base, Ohio, 1981

3. Anon, "PLOT-10, Terminal Control System, User's Manual," Tektronix User's Manual 062-1474-00, Tektronix Inc, Beaverton, Oregon, 1974

4. Anon, "UPDATE Reference Manual", Control Data Corporation publication 60449900, Control Data Corporation, Technical Publication Department, Sunnyvale, California, 1975

5. Newman, J., and Raju, I. S., "Stress Intensity Factor Equation for Cracks in Three-Dimensional Finite Element Bodies," NASA-TM-83200, National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, 1981

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